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TRACKING A TURBULENT SPOT IN AN IMMERSIVE ENVIRONMENT

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Abstract

We describe an interactive, immersive 3D system called *Tracktur*, which allows a viewer to track the development of a turbulent flow. *Tracktur* displays time-varying vortex structures extracted from a numerical flow simulation. The user navigates the space and probes the data within a windy 3D landscape. In order to sustain a constant frame rate, we enforce a fixed polygon budget on the geometry. We supplement the interactive system with interactive, hypertext documentation available on the World Wide Web. In actual use by a fluid dynamicist, the system has yielded new insights into the transition to turbulence in a laminar flow.

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1 Introduction

Turbulence is helpful when it mixes air with fuel in an engine; turbulence is a hindrance when it produces drag on an airplane wing. Thus one would like either to encourage or delay the development of turbulence, depending on the particular situation.

To better understand how laminar flow undergoes a transition to turbulence, a direct numerical simulation (DNS) of a turbulent spot has been performed using supercomputers [Singer]. The resulting dataset contains a wealth of information about the development of the turbulent spot. Our task is to produce an interactive graphical environment in which the scientist can investigate the data.

This paper reports on progress we have made in designing and implementing such a system. The system, *Tracktur*, is specifically designed to help track the development of a turbulent flow.

Section 2 gives an overview of the particular flow problem, outlines the difficulties presented to a visualization system, and describes our general solution. Section 3 describes the 3D environment we use, paying attention to the interaction techniques available to the investigator. Section 4 addresses a serious problem imposed by a real-time system: satisfying a fixed frame rate. We translate the constraint into a fixed polygon budget. Spending that budget wisely requires additional geometric analysis of the flow features.

2 Visualizing the Flow

Simulating the evolution of a turbulent spot has consumed thousands of CPU hours (on a Cray 2, Cray YMP, and YMP C-90 over the course of 2.5 calendar years). The size of the computational grid varies, but 20 million grid points is typical. We wish to animate 230 time steps produced by the simulation, which are archived as hundreds of gigabytes of data.

How does one visualize this large amount of time-varying data at interactive speeds? Massively parallel supercomputers have enough memory to store the data, but they exhibit too much latency in delivering an image across a network to a local workstation. By contrast, graphics workstations can produce the images fast enough, but they do not have enough memory to store all the data.

2.1 The Compression of Data

To solve the visualization problem we applied a new technique that extracts vortices from DNS data. Vortices are the principal features of a turbulent flow, so the volumetric flow field is well represented by the vortex structures within it. These structures are generally shaped like elongated tubes. A tube can be represented economically by a curve (or polyline) through its center and a radius function defining the tube's cross-section over the skeleton curve. A quadrilateral mesh is a natural choice for rendering a vortex tube. The mesh can be easily constructed from the skeletal

representation.

Our extraction technique uses a predictor-corrector scheme to follow a vortex core [Banks3]. Combined with a Fourier representation of the core's cross-section, this technique compresses the data by a factor of 1000 or more – enough to allow it to fit into workstation memory.

Visualization packages from Silicon Graphics (*Explorer*) and NASA (*FAST*) verified that the extraction/compression method works. However, since these systems are not well equipped for interactively investigating the full dataset, we developed our own system. Our system uses a graphics workstation, 3D tracking, and a stereoscopic display to create a virtual 3D environment populated by time-varying geometry.

2.2 The "Windy Landscape"

We are investigating the flow of a viscous fluid over a flat plate. The flow field is numerically perturbed, producing an instability that grows as it convects downstream. The instability develops into a tangle of vortices that constitute a turbulent spot.

In creating a virtual environment, we chose not to model any wind-tunnel apparatus at all. A faithful model of a wind tunnel might be useful for training a wind-tunnel technician, but our target user is the theoretical flow physicist who produced the data. From his perspective, the significant features of the simulation include the flat plate, the fluid flowing over it, the vortex structures, and the units of the computational domain (both spatial and temporal). The combination of a flat plane with a continual flow over it suggested to us a windy landscape.

One of our early design decisions was to make generous use of texture maps to enrich the virtual world. A grid-texture was an obvious choice for the floor, with stenciled textures added over it to denote streamwise units of the domain. To indicate the free-stream velocity, we animate a cloud-texture on two walls in the spanwise directions. We apply two more textures to show the upstream and downstream directions. Surrounded by the textured floor and walls, a viewer is given persistent reminders of the spatial context he is operating within.

In an actual wind-tunnel experiment, the vortex structures would be only millimeters in size, and the free-stream velocity would be about 30 meters per second. The lifetime of the turbulent spot would be less than a second. To compensate for this, we display the 3D animation at more human scales: the geometry is larger and the simulation lasts longer (each by about three orders of magnitude).

3 Interaction Techniques

We have set two primary goals in designing *Tracktur*. First, we want to help the scientist comprehend the spatial evolution of the flow. Second, we want to permit routine measurements of important flow quantities.

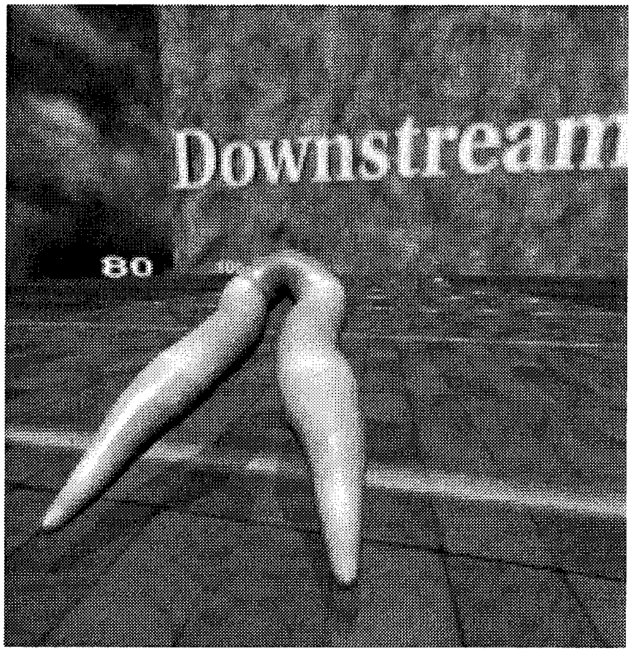

Figure 1: *Initial hairpin vortex moves downstream over a flat plate (t=38). Animated clouds convect downstream at the free-stream velocity. Colors indicate angular velocity.*

Like most immersive systems, *Tracktur* gives the viewer six degrees of freedom in exploring the virtual space. View-centered navigation is expressed through a head tracker or by mouse-and-keyboard inputs. The viewer uses a physical or a virtual 3D pointing device to control the menus, probe the vortex tubes, or grab and reposition the environment.

Since the turbulent spot convects downstream, we give the viewer the option of being convected along with it. This keeps the object of interest within the field of view. The viewer can enable shadows to add another depth cue at only a small penalty in performance [Blinn]. The viewer can select surface, wire-frame, or fat-line representations of the geometry. The fat lines are polylines through the core of the vortices. Their width is adjusted to match the thickness of the tube as seen from a given viewpoint, and they are illuminated as one-dimensional fibers [Banks2].

A menu panel lets the viewer control the temporal component of the 3D animation. There are sliders that set the first and last time steps, and a slider that mirrors the current time step. When the animation is in progress, this slider advances along with the time steps. Alternatively, the viewer can set the current time step with this slider.

The viewer is given a rudimentary tool for examining flow quantities: a data probe. The probe is a ray emanating from the pointing device in the virtual environment. *Tracktur* locates the nearest point on a vortex core to the probe ray, then displays attributes (such as spatial position) of the point.

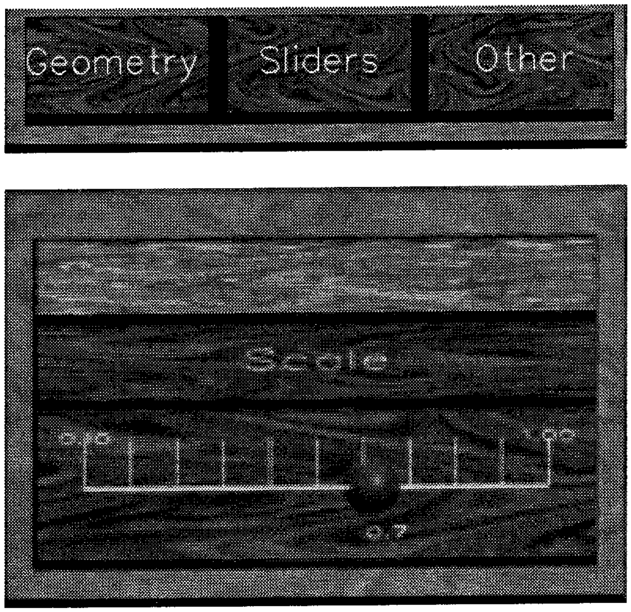

Figure 2: *Textured 3D menu and slider.*

3.1 3D Toolkits

Tracktur is constructed from several component libraries. These include several public-domain toolkits. The Minimal Reality toolkit from the University of Alberta (http: //web.cs.ualberta.ca/ graphics/ MRToolkit.html) provides the basis of a through-the-window interface that uses stereoscopic display and 3D tracking for the head and hand. The CAVE version of the application (shown at SIGGRAPH 94 [Banks1]) uses the graphics library developed by the Electronic Visualization Laboratory (http: //www.ncsa.uiuc.edu:80/ EVL/ docs/ CaveView/ DOCUMENTATION).

We developed a custom file format called *jet* (and a parser for it) to represent the compressed vortex geometry. We also developed a custom toolkit to implement 3D menus, buttons, and sliders (figure 2). These widgets have text labels (using Hershey fonts) rather than icons like the menus in 3dm [Butter]. Buttons and menus can be grabbed and repositioned, and they can be dismissed. The widgets are convected downstream with the view position in order to remain within reach of the viewer during the animation. We apply textures to the widgets as well as to the landscape in order to reduce the cartoon quality of flat-shaded elements.

We also developed a calibration tool for the 3D trackers 3. This tool determines the correct matrix transforms for the trackers. The user interactively aligns a set of coordinate axes on the screen to establish the correct rotation matrix, then the user positions the tracker along the x, y, and z axes of the electromagnetic source. Finally, the tracker is placed at a position that the origin of the screen-space coordinate system will occupy. We move the physical display device out of the way for this measurement so that it will not interfere with the tracker's reported position. The tracker transformations are written to a file and need not be recomputed unless the physical

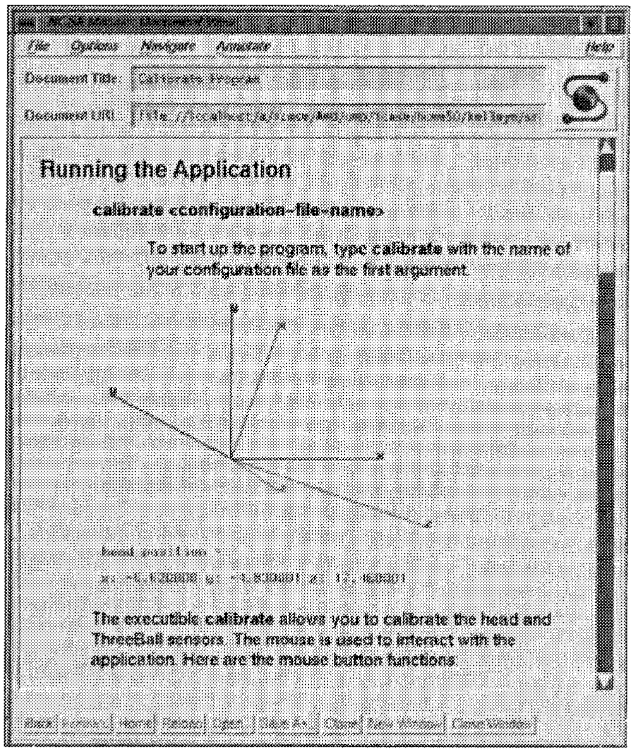

Figure 3: *Hypertext documentation viewed with Mosaic. Page explains how to use the calibration tool for the 3D trackers.*

devices are moved.

3.2 Documentation

The system is being developed at ICASE, which is a very transient environment: most of the researchers hold 2-year postdocs. In order to recruit potential users and developers to sustain the *Tracktur* project, we carried the notion of interactivity from the application to its documentation. A 4000-line hypertext document describes the structure and the operation of the system.

The top node of the document links to the following subjects:

- How to run the application.
- How to interact with the application.
- The CAVE version of the application.
- Libraries used.
- Files and subdirectories used.
- Program bugs.
- Quick reference guide.

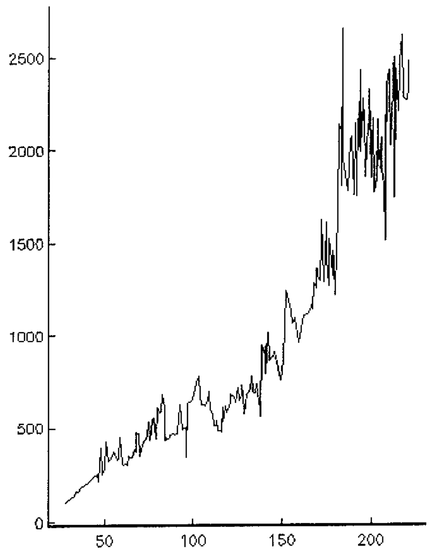

Figure 4: *Number of vortex-skeleton points (vertical) versus time-step of the simulation (horizontal) for the developing turbulent spot.*

One interacts with the dynamic version of the system by running it on a workstation; one interacts with the static version of the system through the hypertext document.

The document, written in HTML (Hypertext Markup Language), is 20 percent as large as the source code developed for the project. The document can be accessed through the World Wide Web (WWW) and viewed under Mosaic. A sample page is shown in figure 3. A hypertext document offers casual users an attractive alternative to traditional man-pages, code comments, and paper archives.

4 The Fixed Polygon Budget

A difficult aspect of developing an interactive system is preserving a fixed frame rate [Funkho]. Our scene-updates are typically dominated by the time spent drawing the vortex tubes. We therefore budget a fixed number of polygons with which to model the geometry of the turbulent spot. The spot increases in geometric complexity as the simulation progresses: the single vortex tube at time 28 develops into about 150 tubes at time 221. On the SGI Onyx with RealityEngine2 graphics, we could sustain about 15 frames per second (stereo) with a fixed count of 9000 polygons.

In the early stages of the simulation, 9000 polygons can represent the vortex geometry more finely than we have computed it (figure 4). We therefore resample the vortex skeleton at a higher spatial resolution in order to exhaust the supply of polygons. But in the late stages of the simulation it is imperative to dole out the polygons in a miserly fashion. The vortex skeletons are down-sampled according to a set of heuristics designed to retain their significant geometric features

(while allowing at least 4 samples in the cross-section of each tube). The re-sampling works as a filter on the original skeletal representation of the vortex core.

The first sample-point is always emitted. After a point is emitted, another point along the skeleton is emitted if any of the following hold:

- the arclength exceeds a threshold;
- the integrated curvature exceeds a threshold;
- the radius of the cross-section changes quickly.

Sometimes a vortex skeleton enters a small spiral from which it never exits. To guard against wasted samples, we reject points on the skeleton where the ratio of the skeleton's radius to its radius of curvature exceeds a threshold (we use the constant 0.7).

Another source of wasted polygons is that there are sometimes redundant copies of a single vortex. These copies are not exact duplicates: the skeletons are only nearly-coincident. To eliminate redundancy, we reject any vortex whose skeleton lies within a set distance of an existing skeleton.

These heuristics are generally effective at maintaining a reasonable amount of geometric detail at the late stages of the simulation.

5 What Has Been Learned

Dr. Bart Singer agreed to use the system to study how a turbulent spot develops. He has learned two new things about the evolution of the turbulent spot. In order to place them in their context, we give a brief descriptive summary of the spot's development.

5.1 How the Turbulent Spot Develops

The turbulent spot begins as a single hairpin vortex (figure 1) produced by a perturbation in the flow near the flat plate (represented by the tile floor). The feet of the vortex drag slowly near the floor while the head reaches into the fast-moving free stream. The original head shears off as a second head develops. New vortices form beneath the legs (figure 5).

In the middle stages of transition, neighboring vortices continue to produce horseshoe-shaped heads between them. The bundle of vortices scours the floor, lifting slow-moving fluid toward the free stream. During episodic bursts of activity the spot is dense with vortices erupting from the floor.

In the late stages of transition (figure 6), the disturbance broadens into a characteristic wedge shape and loses all signs of its initial conditions. It becomes fully turbulent.

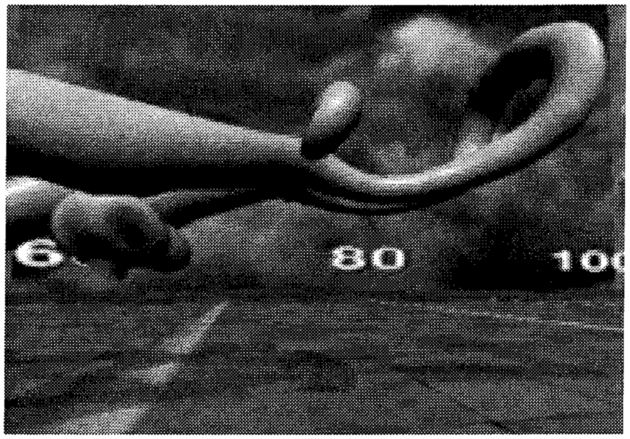

Figure 5: *Vortex head shears off; new head develops behind it; new vortices form beneath legs (t=52).*

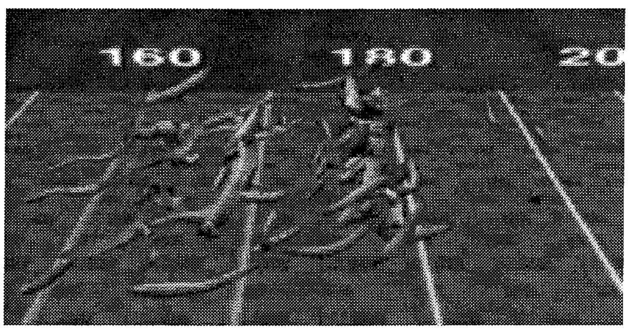

Figure 6: *Late stage: many vortex tubes develop, organizing into wedge-shaped turbulent spot (t=210).*

5.2 Two New Findings

Singer made two new findings about the dataset after using our system. First, he discovered a backwards-tilted S-shaped vortex head in the late stages of transition. The vortex is similar in shape to a structure seen in experimental data for a similar flow. Singer had not observed this feature in the DNS data until he used our system. Evidently, the interactivity permitted him to select the right combination of a particular viewpoint and a particular time step. This could, in principal, have been discovered with the visualization system (FAST) he was a accustomed to using, but with the more limited interactivity it would have been much harder to find.

Secondly, the visualization system gave Singer his first view of the dynamic behavior of necklace vortices. A pair of "necklace" vortices defines the outer extent of the turbulent spot. They eventually shred into pieces, curling into horseshoe and hairpin vortices. Without *Tracktur*, Singer had been unable to track the necklace vortices through their entire history. These findings are initial evidence that the system can assist in the research task.

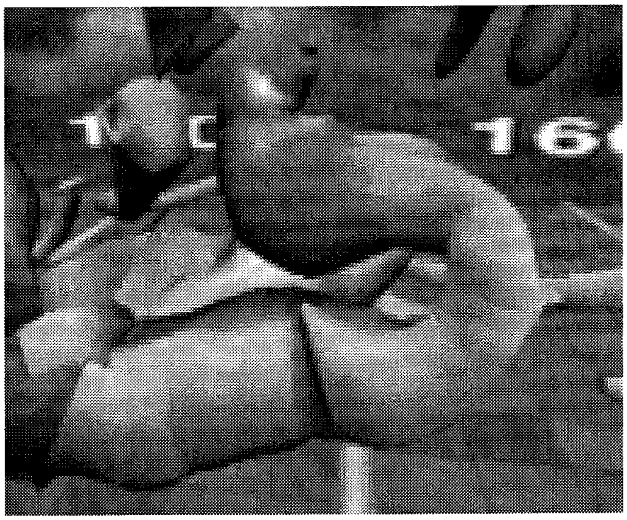

Figure 7: *Backwards-tilted S-shaped vortex head (t=184).*

6 Future Work

There are three major areas of work still to be completed in this project. First, we wish to interpolate the surface geometry during its animation. Morphing one shape into the next is made difficult by the changing topology of the vortex tubes. We would also like to animate the geometry of a single vortex tube so that it actually rotates as it convects downstream. To animate the geometry at this small temporal scale, we need a fast procedural method for deforming the tubes. Second, we wish to provide the viewer with a better way to control the passage of time in the virtual environment. A viewer may want to slow, stop, loop, or reverse the animation while it is progress. Third, we wish to enlarge the set of tools that a viewer may apply to measure quantitative aspects of the flow.

7 Conclusions

Visualization tools can certainly *communicate* research results, but it is not yet clear how well they help *produce* research results. We have created an interactive 3D visualization system, called *Tracktur*, and put it into the hands of the scientist.

The system provides a textured environment for examining the onset of turbulence. The viewer can navigate through the landscape and interact with the turbulent data through 3D menus, buttons, sliders, and a data probe. The system's design and operation are described by an interactive hypertext document. In the hands of a fluid scientist, the system has yielded new insights into the development of a turbulent spot.

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